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1898

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EDITOR'S COMMENTS

Presenting the 2017 Winter issue of the *Journal*. This is an exciting time for science. Studies of the brain are providing new insights into human behavior. Recently the Laser Interferometer Gravitational Wave Observatory (LIGO) measured black hole collisions. I hope that our readers will contribute papers on these topics.

For this issue we have three different papers plus an excerpt from a book by one of our authors. Included here is an excerpt from Peg Kay's first book: *Open Wide and Say AAAAARGH.* All proceeds from the book sales go to the Academy.

Kaelyn Eleuterio, a student at the College of William and Mary, looked into the history of our Junior Academy. Her paper is presented here. Judy Staveley, a professor at Frederick Community College, with her students presents a paper on a new way to generate power in emergency situations. The final paper describes LIGO.

Every year in the Winter issue we publish our list of members. If you see an error in the list, please let the editor know.

Letters to the editor are encouraged. Please send email (wasjournal@washacadsci.org) comments on papers, suggestions for articles, and ideas for what you would like to see in the *Journal*. We are a peer reviewed journal and need volunteer reviewers. If you would like to be on our reviewer list please send email to the above address and include your specialty.

Sethanne Howard

Journal of the Washington Academy of Sciences

Board of Discipline Editors

The *Journal of the Washington Academy of Sciences* has an 11-member Board of Discipline Editors representing many scientific and technical fields. The members of the Board of Discipline Editors are affiliated with a variety of scientific institutions in the Washington area and beyond — government agencies such as the National Institute of Standards and Technology (NIST); universities such as Georgetown; and professional associations such as the Institute of Electrical and Electronics Engineers (IEEE).

Tribute to Isabelle Karle

Dr. Isabelle Lugoski Karle died October 3 at a hospice center in Arlington VA. She was 95. Several colleagues provided moving tributes on her mentorship. Dr. Karle's distinguished Naval Research Laboratory career continues to serve as an inspiration, and NRL honors her and her late husband in so many ways including the Karle Fellows and the Karle Workshops. She was 22 when she got her PhD. Her famous quote on qualities for scientists are similar to another Chemist Iris Lange of Göttingen. She was different from Iris in that she was willing to take risks in working in uncharted areas. the most correct and comforting note in the obituary is her husband's observation about who also merited the Nobel Prize in chemistry that he was awarded (shared with mathematician Herbert Hauptman), and made at the time of the announcement in 1985 : "I can't think of anyone who is more qualified than my wife."

Qualities that are desirable for scientists are curiosity, persistence and dedication. One must not be discouraged by uncharted areas or by lack of acceptance.

Isabella Lugoski Karle

In Loving Memory
December 2, 1921 – October 3, 2017

Isabella graduated from Detroit's Denby High School in 1937. By 1944, she earned a B.S., M.S., and Ph.D. with a specialty in physical science at the University of Michigan. During her long and distinguished career at the Naval Research Laboratory she made pioneering contributions in

determining the three-dimensional structure of molecules and wrote over 250 scientific articles. Among her numerous prestigious honors she received the Bower Award and Prize for Achievement in Science, Francis P. Garvan–John M. Olin Medal, Hillebrand Prize of the Chemical Society of Washington, WISE Lifetime Achievement Award, Gregori Aminoff Prize from the Royal Swedish Academy of Sciences, and the National Medal of Science.

Good and Bad Science Writing

Over the past decade the publishing industry has undergone dramatic changes. The old, proud publishing houses have, for the most part, become virtually indistinguishable from other commercial establishments, delegating their traditional editorial functions to agents whose primary purpose is to meet the demands of the market. Increasingly, authors are eschewing the agent-to-publisher-to-mass market route and are turning to on-demand, self- publishing. Whether the process includes a traditional publisher or not, editorial niceties and fact-checking often have no place in the process.

This has led to a number of problems, the worst of which is – from the Academy's point of view –the great increase in "junk science" being published both as fiction and non-fiction. The Academy therefore offers those Academy members who have written a science-heavy book, the opportunity to submit the book to our editors for review *of the science therein.* The manuscript receives the same rigorous scientific review that we accord articles published in our Journal. If the reviewer(s) determine(s) that the science is accurate, the author may then continue the publishing process of choice and the book will display the seal of The Washington Academy of Sciences. In cases where the Academy editors determine that the book is scientifically accurate but requires editing, they may return the manuscript to the author and request that it be satisfactorily edited.

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One of our members, Peg Kay, has written a series of books each with logo. All proceeds from the sale of her books goes into the Academy coffers. We offer here chapter one from her first book *Open Wide and Say Aaaugh.* Enjoy.

OPEN WIDE & SAY AAAAARGH

PREVIEW

THE OBJECT CODE
a computer program file -- usually a fragment --
that must be linked to the rest of the program to be understood

March 9, 1990

I was shivering up there on the roof, wedged between Don and Lee Roy in the space allotted to the non-performing members of the Laboratory for Industrial Technology staff. We were all a little nervous, all very chilly. That ass Delamain kept mumbling about how nice and brisk it was.

Our group was situated on the near left of the stairs coming up. The Members of the Subcommittee stood to- ward the far left, joined by the Subcommittee staff and the Department of Trade and Industry's Congressional liaison. The NASA brass and the DoTI dignitaries were at the far right. I glanced over at the Subcommittee. Congressman Jaeklin seemed impervious to the chill. Good. I sneaked a peek at the Department's delegation. The Secretary looked frozen and murderous. Not good.

In the no-man's land between the Congress and the Executive, Hump was peering over his belly at the stack of 3x5 crib cards we had prepared for him.

Don nudged me. "If the wind blows those cards out of his hands, we're dead."

Lee Roy leaned over. "Whad'd you say, Clyde?"

Me. "Shhhh."

Hump was standing within a cut-away mockup of a space vehicle. DoTI's graphics department had done a superb job. The controls looked realistic, the 'hull' was heavy enough to withstand the occasional windy blasts, and the scale was big enough to comfortably hold Hump. I had the feeling that a real spacecraft cabin would have fit him like a sausage casing. As it was, he looked impressive – framed nicely by the open door, the Washington Monument at a distance behind him.

At the near left of the roof, Alex was checking the cables to his micro. One last check. One last prayer. At the other end of the cables, in the center of the roof, were the robot arms; next to them was a table laden with various objects; at the far center left, a stool.

Hump cleared his throat loudly and began his speech. "I would like to thank you all for coming here when I know there are warmer, more comfortable places you would like to be. But we thought that you would -- well, never mind that". He turned to the next card.

Steve winced.

"Robot arms are essential to the performance of many tasks, uh, many tasks performed by our astronauts, who, uh, perform many tasks at a distance and require robot arms. So far, these arms have been single arms, each programmed to, uh, perform individual tasks. Devising a way to get two or more arms to work together has been a very stubborn problem -- a problem that NASA had been unable to solve -- at least until they came to my lab."

I looked over at the gaggle of Executive dignitaries.

Now the NASA Administrator looked murderous.

Hump grinned. "When the two-armed robots go up in a spacecraft, they will be driven by much more sophisticated software than what we have here. And there won't be all these cables around for the astronauts to trip over. But the hard work has been done, and the rest is up to NASA. Turn it on, Alex." Hump put the unread cards in his jacket pocket and folded his arms across his paunch.

Alex typed the robot's name, 'The Dentist', onto the keyboard. The micro whirred, the cables transmitted the commands and the robot arms swung toward the table. One arm picked up a glass jar and carried it toward the other arm, which moved in and deftly untwisted the cap. The arms set the jar and cap gently down on the table.

Congressman Jaeklin applauded.

Unnoticed by the multitude, Alex made an 'aw, it was nuthin' gesture. He really was cute.

Now the arms swung toward their next task – the stool. Abruptly, they paused, changed direction, and accelerated toward a figure standing at the edge of the roof.

I closed my eyes. Opened them again. *Oh, my God, no!*

Stop!

Closing the Sputnik Gap

Introduction to the History of the Junior Academy

In 1957 the then Soviet Union launched a small satellite into low Earth orbit. It lasted about a year before burning up in the atmosphere. History changed with that launch. The United States realized it was behind in what came to be termed the "space race". Apparently the press had a field day discussing the scientific gap under which the US was suffering. Everyone wanted to know what it took to keep a body in orbit about the Earth. The people who knew that answer were authorities in celestial mechanics. The US had four such people: *Paul Herget* at Cincinnati who was the world's expert on orbits of minor planets; *Ray Duncombe* at the US Naval Observatory who was the expert on planetary positions and precise positions of stars; *Dirk Brouwer* at Yale who had the best handle on the theory of orbits and co-author of the 1961 book *Methods of Celestial Mechanics*; and *Leland Cunningham* at UC Berkeley who was expert on the precise measurements of the orbits of comets, planets, satellites, and space probes. He was also an early authority on electronic digital computers and assisted in their construction and use in orbit calculations. These four were held hostage by their phones answering eager questions from the press which seemed to them like queries from Boy Scouts working towards a merit badge. Orbit theory is rather elementary in celestial mechanics.

There just were not enough teachers to train the plethora of students with a new interest in celestial mechanics. Given the dearth of experts in celestial mechanics companies hired mathematicians who promptly rediscovered the works of Laplace and Gauss that were over a century old. They learned that one can get a preliminary orbit from three observations of the right ascension and declination of a satellite. These observations were the six known quantities from which one can produce the six quantities that define an orbit. The big computers could get an orbit in ten seconds what took Leland Cunningham eight hours with a hand calculator.

By 1965 Georgetown University's celestial mechanics course blossomed to over fifty-five students taken from many government agencies in the DC area. Dirk Brouwer at Yale established several summer institutes in dynamical astronomy to train students. The one at Yale is still active. Thus by 1969 we put humans on the Moon.

There never was a real science gap. The information was there, captured in books and astronomical observatories. It was safely kept in the minds of scientists quietly teaching their students. The lack, perhaps, is that the importance and excitement of science were not part of our national identity. To address that issue, the Washington of Academy of Sciences worked with scientists and teachers in the DC metro area to bring students to science. Ms Eleuterio shares with us in the next pages the beginning of the Junior Academy of the Washington Academy of Sciences.

A Brief History of the WAS Junior Academy

Kaelyn Eleuterio

College of William and Mary

Abstract

In 1952 the Washington Academy of Sciences (WAS) created a program for high school students in the D.C., Maryland, and Virginia area, named the Junior Academy of Sciences. The Junior Academy was created in response to the general lack of young people interested in science at the time. Members were selected based on their achievements in science fairs and science talent searches. Although it was "officially" supervised by members of The Committee on Encouragement of Science Talent (from WAS), the student officers ran the meetings themselves with little adult oversight. These meetings gave them the opportunity to discuss possible solutions to the general lack of young people interested in science. Members also presented their own papers in an annual lecture series (where they were ranked by other students and could receive scholarships), took monthly railroad trips to Philadelphia or New York to visit scientific demonstrations and museums, and helped run the annual D.C. Science Fair, among other activities. Many members of the Junior Academy became scientists themselves, and the club is still active today, often partnering with other programs for young students.

Introduction

DURING THE 1940S AND 50S the United States had a major problem: young students were no longer interested in science or math, thus scientists would not have anyone to continue their legacy. Scientists and science lovers alike raced to find a solution; and it came in an unexpected way: with a small group made up of Mrs. Grace Truman; Dr. Marvin, president of George Washington University; and Reverend J. Hunter Guthrie, S.J., president of Georgetown University. This group first proposed a Junior Academy of Sciences, a student group based on the Washington Academy of Sciences (WAS). After six years of careful planning, the club was finally brought to fruition on June 13, 1952.

So how does one create a club that encourages young people to engage in science, while also giving the members opportunities for leadership? To make it more egalitarian, the Junior Academy was open to all the members of science clubs of about 240 high schools (public and

private) in D.C., Maryland, and Virginia. The Junior Academy also selected members based on merit (some members had ranked in science fairs, while others had been noticed during science talent searches). Although the Junior Academy was "officially" supervised by members of The Committee on Encouragement of Science Talent (a committee of WAS), the student officers ran the meetings themselves with little adult oversight. The WAS members didn't even preside at the annual election of Junior Academy officers. The Junior Academy also held a few joint meetings with the WAS during the Spring, which both served to encourage them to pursue science, and recognized the merits of select high school students (who received Certificates of Merit to recognize accomplishments demonstrated in the Westinghouse Science Talent Search).

The newly-formed Junior Academy included student officers (from high schools in the D.C. area), alumni members (students who had attended local high schools), and Fellows (either teachers whose students had impressive scientific accomplishments, or scientists who promoted science education). All of the Junior Academy activities were guided by a Governing Council, made up of the student officers, alumni members, and Fellows. The Council also included both membership representatives as well as members of the Committee on Encouragement of Science Talent (one of WAS' committees).

Beginning with its conception in 1952 and continuing far into the 1960s, the Junior Academy responded to the concerning lack of scientists by promoting science clubs in local high schools. For example the presidents of school science clubs met with Junior Academy officers to discuss common problems in science promotion, such as the lack of stimulation from science fair projects. The Junior Academy also held annual science club workshops at Georgetown University, which about 200 students and adults attended. During these workshops participants had a short general meeting followed by six simultaneous discussion groups to talk about different problems in science clubs. Each group had a student chairman, a secretary, and an adult advisor. The science club workshop closed with an assembly where each group presented a report on their conclusions.

However, these are just a few of the Junior Academy's many activities. Here are a few more.

Meetings

The Junior Academy met regularly at Georgetown University, and they usually discussed problems they noticed in the science community, or ways to encourage other students to be more interested in science careers. Guest scientists would come to lecture on findings in their field of expertise or present papers, Junior Academy students presented summer opportunities for research in the D.C. area to their fellow members, and they occasionally allied with local scientists for special trips (like a telescopic tour of the moon with the National Capital Astronomers). Every Fall the students had an organizational meeting in the Hall of Nations of Georgetown University, and the year closed with a Spring election meeting (when they elected new officers and the National Science Fair finalists presented papers on their projects).

The Annual Christmas Lectures

Years before the Junior Academy's conception the Philosophical Society of Washington had held an annual Christmas Lecture for Young People. During Christmas break a scientist or professor would give a lecture about their research to high school students in the D. C. area.

However, the Junior Academy eventually took over the Christmas lectures, and held them in Georgetown University's main hall. For example one of the Junior Academy-organized lectures included lectures from professionals in physics, chemistry, biology, and mathematics; a banquet; a slide presentation on the year's activities; and an address by John D. Nicolaides, special assistant to the director of the Office of Space Sciences and Applications.

However, the Junior Academy eventually decided to allow students to present their own papers. Junior Academy members judged each paper; the winners received scholarships of a few hundred dollars. As Reverend Francis J. Heyden, S.J. (one of the former chairmen of the Junior Academy, who had a lot of influence on many student members) said in his memoirs, *Earth Science,* "The hall seated 800 and there were not many empty seats. The Junior Academy had a great sense of pride."

The Junior Academy published the extended abstracts of the student papers in an annual publication called *Proceedings of the Washington*

Junior Academy of Sciences. Copies were distributed to each member of the Junior Academy and some members of the WAS. The Junior Academy also distributed copies among the libraries of the senior high schools in the D.C. area, in order to have a permanent record of local scientists' achievements, as well as to encourage budding high-school scientists to pursue science careers.

Railroad Trips

On one Saturday of each month, nearly a thousand students and teacher chaperones took an excursion to Philadelphia or New York to visit scientific demonstrations and museums (such as the Fels Planetarium, Franklin Institute, and Academy of Natural Science). They took the Pennsylvania Reading Railroad (now called Amtrak), and the students all paid for their own way; however, the railroad also donated a generous sum every year that covered the Junior Academy's other expenses and create small scholarships.

D.C. Science Fair

Before the Junior Academy was created WAS held an annual D.C. Science Fair every spring (starting in 1947) with the aid of the D.C. Board of Education, the Science Service, and other science societies. However, the Junior Academy took over the Science Fair soon after it was created. The WAS Committee on Science Fairs continued to create policies for the Fair, find judges, get publicity, and raise any needed funds that were not provided by the school boards or other sources of income. However, the Junior Academy also relied on the generosity of local scientists. Reverend Heyden writes in his memoir that each science fair had about 125 judges, and that many of them needed to take time off from their jobs to judge, often without compensation. "In all there must have been at least a dozen science fairs for the greater Washington area and the same judges often covered two or three Fairs. It is hard to realize how self-sacrificing judges had to be..." Heyden wrote. The Science Fair was open to all students in local junior and senior high schools, and winners in grades 9-12 automatically became Junior Academy members (as of 1954). Select students who placed in the Fair also went on to represent D.C. at the National Science Fair held in May.

Inspired by the D.C. science fair, other counties in the greater D.C. area began holding local science fairs (such as the Prince Georges County Science Fair or the Arlington Science Fair), and sent a few students to the D.C. Science Fair every year. Although the Junior Academy itself wasn't involved in planning these local fairs, they guarded the exhibits while the forty winners met with a science talent search for questioning or seminars. The winners often formed close friendships with the Junior Academy members and they were invited to a panel with expert scientists on the Georgetown University Forum on 13 TV and 400 radio stations. The winners, along with a selected group of six Junior Academy members, were also sent to the national meeting of the Junior Science and Humanities Symposium for the greater Washington area (sponsored by the U.S. Army).

Conclusion

The Junior Academy is still strong today, and is a partner of the Senior Scientist and Engineers STEM Volunteer Program (run by the American Association for the Advancement of Science, or AAAS). Junior Academy members also work with Sigma Xi in its new publication "Chronicle of the New Researcher," and supports a maker space in Maryland (which FIRST Robotics organizes).

The Junior Academy was one of the first attempts to make students passionate about science, and it succeeded: many members went on to be scientists themselves, and have fond memories of the club. One reason for its success is that its members had so much responsibility: students planned most of the activities themselves, which made them more invested in the events and meetings. Many of the adult chairmen let the students lead themselves, especially Reverend Heyden.

Heyden writes that before the space age, "science interest waned…for almost twenty years. The schools…the teacher[s] [of] colleges, science clubs, and courses in elementary schools saw a general lack of interest." However, programs like the Junior Academy and the arrival of the new Vanguard satellite made students passionate about science and technology once again – to the point where scientists were even rushing to find new topics to feed the students' interest. As Heyden concluded in his memoir: "Researchers are working at wits' end to keep up with the…inquiring minds…this is a good sign for progress and a release from

the quicksands of crystallized complacency." Thus, the success of the Junior Academy provides a model for modern scientists who hope to make students interested in STEM: open the club to a wide range of students, encourage them to talk about the problems they personally see in science, and let them plan the activities they're interested in. It may be out of most scientists' comfort zone, but isn't science about taking risks?

Bio

Kaelyn Eleuterio is a sophomore at the College of William and Mary. She has participated in the Science and Engineering Apprentice Program (SEAP) and Pathways Internship Program, both at the Naval Research Laboratory (NRL) in D.C. She gives special thanks to Vijayanand Kowtha of IEEE and Terry Longstreth of the Washington Academy of Sciences, for primary documents that were used for this article.

Use of Microbial Fuel Cells for Power Generation in Emergency Situations

Tanner Ash, Elizabeth Doyle, Godfrey Ssenyonga, Cassie Kraham, Sean Scott

Faculty: Judy Staveley, Adil Zuber

Frederick Community College: Bioprocessing Technology Program

Abstract

Bioelectrogenic microorganisms can generate electricity in emergency situations (*e.g.* natural disasters) if traditional sources of power are unavailable. When coupled with a fuel cell, these microorganisms offer a promising source of alternative energy for use in adverse conditions. A microbial fuel cell was constructed and tested in both laboratory and field-based conditions. Our preliminary testing demonstrated promising results on the utility of this novel alternative source of energy.

Introduction

MANY COUNTRIES LACK ELECTRICITY and the U.S may also be heading towards an energy crisis. Only 5.1% of South Sudan's population has access to electricity. Less than 20% of the populace have access to electricity in many countries (*e.g.* Tanzania, Niger, Sierra Leone, Burkina Faso, Central African Republic, Liberia, Malawi, Burundi, Chad) (World Atlas, 2017). Electricity is a highly valuable utility in the modern world used for - but not limited to - lighting, medicine, refrigeration, and computers. The availability of electricity for these applications is even more important in emergency situations such as natural disasters and military conflicts when traditional electric sources may not be available.

Bioelectrogenesis is the generation of electricity by biological mechanisms and processes. Some soil-based bacterial species generate electricity, similar to the well-known electric eel. These bioelectrogenic microorganisms can be coupled with electrodes to create microbial fuel cells (MFC) that generate electricity. MFCs have been the subject of extensive research.

MFCs extract electrons from microbial life generated by cellular respiration. Given the ubiquity of microbial energy sources, this technology has the potential for near-worldwide utility. A MFC device can readily be

constructed from inexpensive materials using microorganisms to generate electricity. For the MFC to function properly, electrons must flow via an electric current from one electrode to the other electrode.

Construction of a MFC requires cultivation of a diverse microbial population. Several microbial species are known to be bioelectrogenic. The bacterial genus *Shewanella* is ubiquitous around the world. The anaerobic bacterial *Geobacter* genus is commonly found in deep soil underground or in ocean sediments. While Protozoa are not specifically bioelectrogenic, this common class of eukaryotes play a key role in maintaining the balance of microbial life needed to support a population of bioelectrogenic organisms. Sufficient nutrients must also be present in the environment to allow microbial population to grow. Carbohydrates and organic nutrients found in soil are consumed by microbial cellular respiration and producing electrons. These electrons are then released back into the soil. Our work was based upon the existing concept of the properties of bioelectrogenic microorganisms for generating power in emergency situations.

Materials and Methods

- Two standard beakers and / or two plastic containers
- Two Zinc strips and Two Copper strips.
- Electrodes – Anode and Cathode wires with multimeter tests AC & DC, Resistance, Diode and Transistor hFE (0-1000). The switch dial allows for 19 ranges. This multifunction digital meter can be bought at any electrical or home store (Lohner, 2016).
- Electrical Tape
- Rope
- Conductors
- Soil (Several different types)
- *Shewanella* Bacteria

The MFC is constructed of a mud-filled container populated by microorganisms. The mud originated from a local pond containing wastewater. The MFC has two compartments, an anode and cathode, separated by a selectively-permeable membrane for positively-charged ions. Organic matter is oxidized by microorganisms to generate electrons. The electrons transmit via an electronical circuit to the cathode. Protons

pass through the selectively-permeable membrane. The electrons and protons combine with oxygen to form water.

Anode: Anodic materials must be conductive, biocompatible, and chemically stable.

Cathodes: Water or Copper

Membrane. The majority of MFC designs require the separation of the anode and the cathode compartments. In addition to conventional instruments used for chemical measurements in microbial systems, the MFC experiments required specialized electrochemical instrumentation for testing.

Results

"Electric Resistance (Ohms)"

Table 1 Outside					
DATE	LOCATION	DCV (10)	ACV (10)	Electric Resistant (Ohms)	Observations
4/20/17	Garden	2.5	0	1k	Temp 80 degrees F, partly cloudy
12:10 pm					Ground was wet from previous rain
7:30 pm	Garden	2.5	1.8	1k	Temp 82 degrees F, cloudy
					Light rain
4/21/17	Garden	4	1.3	90	Temp 80 degrees F, sunny
2:00 pm					Ground was wet from previous rain
					Debris around site, bent
Beaker #1					
DATE	LOCATION	DCV (10)	ACV (10)	OHMS (x10)	Observations
3/21/17	Lab			3.9	Red on Cu
				4.5	Black on Zn

				7	Farther apart
					500 mL organic soil
4/10/17	Lab			0.5	Temp 69.5 degrees F No water since 3/21/17; soil still moist
					Added conductor produced max output
					Added DI water to 100 mL after reading
4/11/17	Lab	5	1.4		
4/13/17	Lab	3	1	1k	Moved Cu and Zn
					Added soil 100 mL - 500 mL
					No water added
4/17/17	Lab	3	1.2	1k	Reading higher without water
4/19/17	Lab	4	1.7	60	Temp 68.5 degrees F in room; colder weather
					500 mL soil, packed; visible separation between old and new
					Cu was moved deeper into the soil
					Put in 37 degree C incubator after reading
4/20/17	Lab	4	1.1	100	From 37 degree C incubator

Beaker #2					
DATE	LOCATION	DCV (10)	ACV (10)	OHMS(x10)	Observations
4/19/17	Office	1	0.2	1k	No water since 3/21/17
6:00 pm					Covered with bag
					Colder weather

					Added 45 mL of DI water and 10 mL of table sugar to 500 mL of organic soil; covered and placed in 37 degree C incubator
4/20/17	Lab	2	0.9	1k	24 hours later

Ohmic Losses: The ohmic losses (or ohmic polarization) in the MFC include both the resistance to the flow of electrons through the electrodes and interconnections, and the resistance to the flow of ions.

Power: The overall performance of an MFC was evaluated in different ways but mainly through power output.

Energy Efficiency: The most important factor for evaluating the performance of the bionano cell for making electricity which is compared to more traditional techniques, is to evaluate the system in terms of the energy recovery.

The MFC is a new approach that represents new technology for generating bioelectricity from biomass and microorganisms. In the MFC, the bacteria and organic matter produce electrons that travel and generated small amounts of electricity.

Conclusion

Bacterial extracellular electron transfer can be a promising tool to use and convert chemical energy into electricity through electrochemical devices called microbial fuel cells, which combine hydrogen and oxygen to produce small amounts of clean electricity. Microbial fuel cells are a new promising technology for power generation for emergency situations across the globe.

The MFC design requires additional work before prototyping can begin. Optimization of soil composition and improvements in MFC fabrication require additional studies. While still preliminary, this technology does offer the potential for availability of an alternative electricity resource in resource limited and emergency situations.

Acknowledgements

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Biography

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THE LIGO CHIRP

Sethanne Howard

USNO retired

Abstract

The story of the LIGO chirp, gravitational waves, and the recent detections of merging black holes and neutron stars.

Introduction

The Laser Interferometer Gravitational-Wave Observatory (LIGO) is a large-scale astrophysics experiment and observatory to detect cosmic gravitational waves and to develop gravitational-wave observations as an astronomical tool. This single sentence contains a plethora of interesting concepts.

Let us start with gravitational waves. Newton's 17th century universe did not allow gravitational waves. According to Newton space is filled with gravity at all places all at once. Einstein's 20th century spacetime universe does allow gravitational waves. Gravitational waves are 'ripples' (waves) in the fabric of spacetime that propagate at the speed of light. The General Theory of Relativity (GTR) allows spacetime to ripple. Einstein's equations are the core of GTR. They describe the relation between the geometry of a 4-dimensional spacetime and the energy–momentum contained in that spacetime.[i] The Einstein field equations are nonlinear and very difficult to solve. The equations can be written:

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

where the symbols with subscripts are tensors; T is the energy momentum tensor; G is the Einstein tensor which expresses the curvature of the manifold; g is the metric tensor; Λ represents the cosmological constant. The left side represents the spacetime. The right side represents the matter.

In GTR gravity results from the curvature of spacetime, and spacetime curves in the presence of mass. Figure 1 is a two dimensional representation of this. Mass distorts the spacetime around it. As objects with mass move around in spacetime, the curvature changes to reflect the motion.

In certain circumstances mass that accelerates disrupts the changing curvature creating gravitational waves. If the accelerating mass is very large, then spacetime is disrupted in such a way that waves of distorted spacetime radiate from the source.

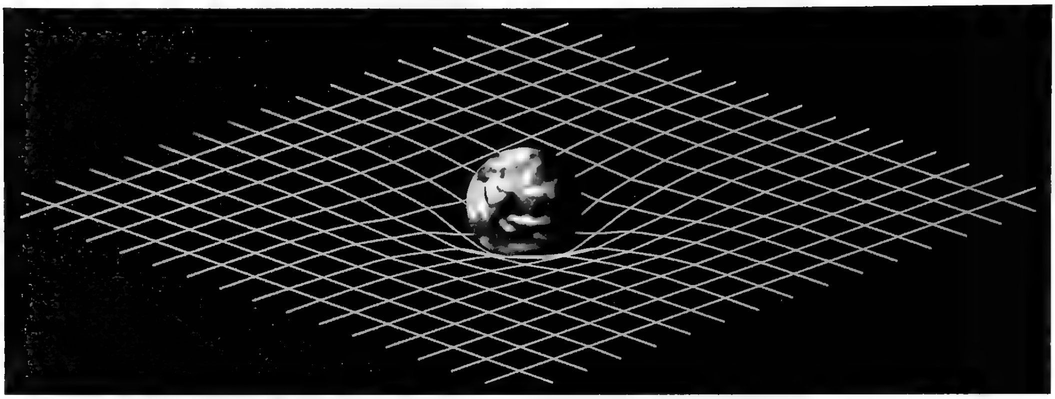

Figure 1 two dimensional representation of space-time curvature

Einstein was not the first to suggest gravitational waves. In 1905 Henri Poincaré proposed gravitational waves, emanating from a body and propagating at the speed of light, as required by the Lorentz transformations[ii] . He suggested that, in analogy to an accelerating electrical charge producing dipole electromagnetic (EM) waves, accelerated masses in a relativistic field theory of gravity should produce gravitational waves. When Einstein published his GTR in 1915, he was skeptical of Poincaré's idea because the GTR theory implied there were no gravitational dipoles to produce waves. An accelerating electric charge will produce dipole radiation. An accelerating mass will not produce dipole waves. So the analogy breaks down.

This led to extended controversy over choice of coordinate systems. Things resolved in 1956 when the equations of GTR were cast in terms of the observable Riemann curvature tensor $R_{\mu\nu}$ where μ and ν each take the values 0, 1, 2, 3. There is no gravitational dipole radiation. Known as the Einstein field equations, these equations specify how the geometry of space and time is influenced by whatever matter and radiation are present.

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu} .$$

A Small Digression into Math

In 1828 Carl Friedrich Gauss proved an important property of Euclidean surfaces. The theorem says that the curvature of a surface (how curvy it is) can be determined entirely by measuring distances along paths on the surface. That is, the curvature does not depend on how the surface might be embedded in a 3-dimensional space. Bernhard Riemann extended Gauss's theory to higher-dimensional spaces called *manifolds* in a way that also allows distances and angles to be measured and the notion of curvature to be defined, again in a way that was intrinsic to the manifold and not dependent upon how it was embedded in higher-dimensional spaces. This discovery caused a major paradigm shift in mathematics; it freed mathematicians from the belief that Euclid's axioms were the only way to make geometry consistent and non-contradictory. Through his pioneering contributions to differential geometry, Riemann laid the foundations for the mathematics of GTR.

Riemann found the correct way to extend the differential geometry of surfaces into n dimensions. The fundamental object is called the *Riemann curvature tensor*, $R_{\mu\nu}$. Riemann's idea was to introduce a collection of numbers at every point in space (*i.e.*, a *tensor*) which would describe how much the space was bent or curved. Riemann found that in four dimensions, one needs a collection of ten numbers at each point to describe the properties of a manifold, no matter how distorted it is.

Near the Earth the Universe looks roughly like 3-dimensional Euclidean space – flat[iii]. However, near very massive stars and black holes spacetime is curvy. The amount that spacetime curves can be estimated by using theorems from Riemannian geometry. The Riemann curvature tensor is given by:

$$R(u,v)w = \nabla_u \nabla_v w - \nabla_v \nabla_u w - \nabla_{[u,v]} w$$

where $[u, v]$ is the Lie bracket of vector fields. Or in terms of Christoffel[iv] symbols:

$$R^{\rho}_{\sigma\mu\nu} = \partial_u \Gamma^{\rho}_{\nu\sigma} - \partial_v \Gamma^{\rho}_{\mu\sigma} + \Gamma^{\rho}_{\mu\lambda}\Gamma^{\lambda}_{\nu\sigma} - \Gamma^{\rho}_{\nu\lambda}\Gamma^{\lambda}_{\mu\sigma} \,.$$

Clearly this does not give us an equation that is straightforward to solve. Nevertheless this is as far as we shall go with Riemann. The curvature tensor exists and provides the framework for gravitational waves.

Tensors are particularly useful for describing the properties of a substance where its properties vary in direction. An example would be the stress and strain in a bent metal bar. The stress and strain vary with the direction along or across the bar. A tensor α_{ij} is called a tensor of second rank, because it has *two* indices. A vector — with *one* index — is a tensor of the first rank, and a scalar — with no index — is a tensor of zero rank.

A *metric space* is a set, X, for which distance $d(x, y)$ is defined for every pair of points (x, y) belonging to X. A *metric tensor* is a function which takes as input a pair of tangent vectors v and w at a point of a surface (or higher dimensional differentiable manifold) and produces a real number scalar $g(v, w)$ in a way that generalizes many of the familiar properties of the dot product of vectors in Euclidean space. In the same way as a dot product does metric tensors define the length of and angle between tangent vectors. Through integration the metric tensor allows one to define and compute the length of curves on the manifold. The metric captures all the geometric and causal structure of spacetime. The metric tensor describes the local geometry of spacetime.

A Euclidean (flat) metric tensor using the typical x, y coordinates is:

$$g = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}.$$

The length of a curve in Euclidean space is familiar:

$$L = \int_a^b \sqrt{(dx)^2 + (dy)^2}.$$

Then in special relativity (still a flat space) the metric tensor includes time and becomes

$$g_{\mu\nu} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{bmatrix}.$$

The spacetime interval becomes

$$ds^2 = c^2dt^2 - dx^2 - dy^2 - dz^2 = g_{\mu\nu}dr^{\mu}dr^{\nu} .$$

The simplest metric for a black hole is the Schwarzschild metric:

$$g_{\mu\nu} = \begin{bmatrix} -\left(1-\dfrac{2GM}{rc^2}\right) & 0 & 0 & 0 \\ 0 & \left(1-\dfrac{2GM}{rc^2}\right)^{-1} & 0 & 0 \\ 0 & 0 & r^2 & 0 \\ 0 & 0 & 0 & r^2\sin^2\theta \end{bmatrix}$$

Even in the simplest case, a curvy spacetime is complicated.

Gravitational Waves

Einstein's equations expressed with the Riemann curvature tensor and a metric will produce gravitational waves. These are traveling distortions of spacetime moving at the speed of light. The ripples are subtle; after starting at some curvy spacetime by the time they reach Earth some gravitational waves compress spacetime by as little as one ten-thousandth the width of a proton. As a gravitational wave passes an observer, that observer will find local spacetime distorted by the effects of strain. Distances between objects increase and decrease rhythmically as the wave passes, at a frequency corresponding to that of the wave. Figure 2 shows a greatly exaggerated effect on a circular ring of particles. This effect occurs despite that the ring is not subjected to an unbalanced force. The magnitude of this effect follows an inverse square law. The two figures illustrate the exaggerated squeeze and stretch caused by the gravitational wave.

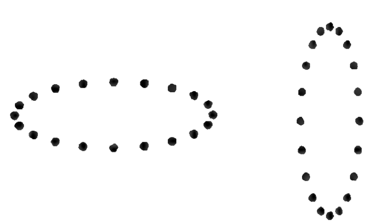

Figure 2 the exaggerated effect of a gravitational wave passing a ring of particles – stretch on the left and squeeze on the right

As with other waves, there are characteristics that describe a gravitational wave:

- Amplitude: h, this is the size of the wave: the fraction of stretching or squeezing. The amplitude shown in Figure 2 is roughly $h = 0.5$ (or 50%). Gravitational waves passing through the Earth are many sextillion times weaker than this — $h \approx 10^{-20}$. This is because the sources of the waves are distant from Earth.
- Frequency: f, this is the frequency with which the wave oscillates (the inverse of the time between two successive maximum stretches or squeezes).
- Wavelength: λ, this is the distance along the wave between points of maximum stretch or squeeze.
- Speed: This is the speed at which a point on the wave (*i.e.*, a point of maximum stretch or squeeze) travels. For gravitational waves with small amplitudes, this wave speed is the speed of light (c).

The speed, wavelength, and frequency of a gravitational wave are related by the equation $c = \lambda f$, just like the equation for a light wave.

Polarization of a gravitational wave is similar to the polarization of an EM wave except that the polarizations of a gravitational wave are 45° apart, as opposed to 90° for EM radiation.

Gravitational waves because they represent curved space can penetrate regions of spacetime that EM waves cannot. EM waves cannot *see* curved spacetime. Gravitational waves can *see* curvy spacetime. So we can, for example, observe the merger of black holes and possibly other exotic objects that occur in curvy spacetime. In particular gravitational waves can offer a possible way of observing the very early Universe. This is not possible with conventional astronomy, because before recombination the Universe was opaque to EM radiation.

Objects that are accelerated radiate gravitational waves, provided that the motion is not perfectly spherically symmetric (like an expanding or contracting sphere) or rotationally symmetric (like a spinning disk or sphere). Two objects orbiting each other, as a planet would orbit the Sun, will radiate. In extreme cases massive stars like neutron stars or black holes, orbiting each other quickly, give off significant amounts of gravitational

radiation. Figure 3 is an artist's conception of gravitational waves. A good source for an explanation is http://phdcomics.com/comics.php .

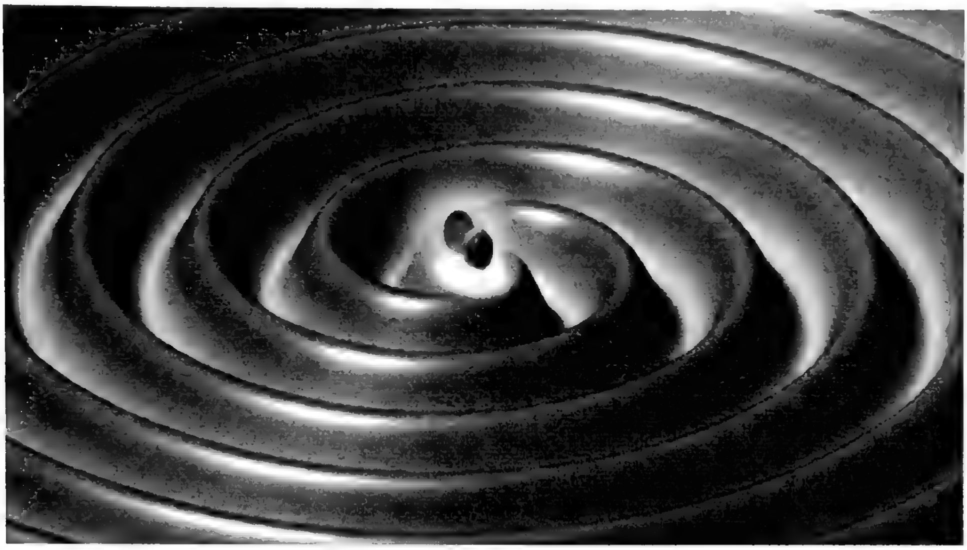

Figure 3 artist's conception of gravitational waves

In principle gravitational waves could exist at any frequency. However, very low frequency waves would be impossible to detect, and there is no credible source for producing detectable waves of very high frequency. Stephen Hawking and Werner Israel[v] listed different frequency bands for gravitational waves that could plausibly be detected, ranging from 10^{-7} Hz up to 10^{11} Hz.

First proof of gravitational waves

Actual proof did not arrive until 1974, 20 years after Einstein's death. In that year two astronomers, Russell Alan Hulse and Joseph Hooton Taylor. Jr., working at the 305 m radio antenna at Arecibo Radio Observatory[vi] in Puerto Rico detected pulsed radio emissions and thus identified the source as a pulsar, a rapidly rotating, highly magnetized neutron star[vii] that emits a precise pulsed signal. The neutron star rotates on its axis 17 times per second; thus the pulse period is 59 milliseconds. After timing the radio pulses for some time, Hulse and Taylor noticed that there was a systematic variation in the arrival time of the pulses. Sometimes, the pulses arrived a little sooner than expected; sometimes, later than expected. These variations changed in a smooth and repetitive manner, with a period of 7.75 hours. The pulses from the pulsar sometimes arrive 3 seconds early

relative to others, showing that the pulsar's orbit is 3 light-seconds across[viii], approximately two-thirds of the diameter of the Sun. They realized that such behavior is predicted if the pulsar were in a binary orbit with another star, later confirmed to be another neutron star. Their discovery of the system and analysis of it earned them the 1993 Nobel Prize in Physics "for the discovery of a new type of pulsar, a discovery that has opened up new possibilities for the study of gravitation."

This is the binary pulsar, PSR B1913+16, which was exactly the type of system that, according to GTR, should radiate gravitational waves – massive stars orbiting each other with a steady decay in the orbit. Knowing that this discovery could be used to test Einstein's prediction, astronomers began measuring how the period of the stars' orbits changed over time. After eight years of observations it was determined that the stars were getting closer to each other (the orbit was decaying) at precisely the rate predicted by GTR. Since this is a binary system,[ix] the masses of the two neutron stars can be determined, and they are each about 1.4 times the mass of the Sun. Observations have shown that the pulsar's orbit is gradually contracting (and therefore accelerating), which means there is emission of energy in the form of gravitational waves, as described by GTR, causing the pulsar to reach periastron slightly early. Also, the periastron advances 4° per year in longitude due to the gravitational field (thus the pulsar's periastron moves as far in a day as Mercury's moves in a century).

This system has now been monitored for over 40 years and the observed changes in the orbit agree so well with GTR, there is no doubt that it is emitting gravitational waves. See Figure 4.

The total power of the gravitational radiation (waves) emitted by this system presently is calculated to be 7.35×10^{24} watts. For comparison this is 1.9% of the power radiated in light by the Sun (another comparison is that the Solar System radiates only about 5000 watts in gravitational waves). The mass of the companion is 1.387 $M_\odot$, the total mass of the system is 2.828378(7) $M_\odot$, the orbital period is 7.751938773864 hours (yes, all those digits are real), the eccentricity is 0.6171334 the semi-major axis is 1,950,100 km, the periastron separation is 746,600 km, and the orbital velocity of stars at periastron (relative to center of mass) is 450 km/s.

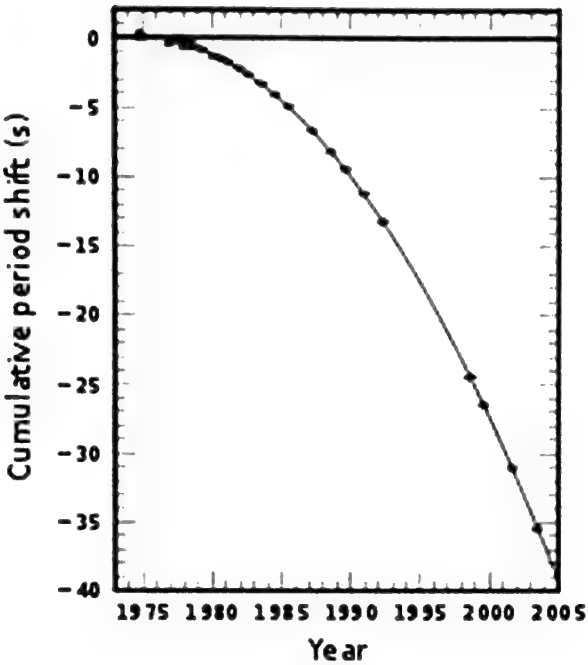

Figure 4 Orbital decay of PSR B1913+16. The data points indicate the observed change in the epoch of periastron with date while the parabola illustrates the theoretically expected change in epoch according to GTR.

The Distance Problem

The strongest gravitational waves are produced by catastrophic events such as colliding black holes, the collapse of stellar cores (supernovae), coalescing neutron stars or white dwarf stars, the slight wobbly rotation of neutron stars that are not perfect spheres, and the remnants of gravitational radiation created by the birth of the Universe itself.

However, these sources are far away from Earth. The effects when measured on Earth are predicted to be very small, having strains of less than 1 part in 10^{20}. Therefore a detector on Earth would need to be extremely sensitive. Such detectors are not off the shelf items.

Joe Weber (1919-2000) was an American physicist who helped develop the first maser and laser. Weber was also the first to make a real attempt to detect gravitational waves. He worked at the University of Maryland.

He developed the first gravitational wave detectors (Weber bars) in the 1960s, and began publishing papers with evidence that he had detected these waves. In 1972, he sent a gravitational wave detection apparatus to the moon (the "Lunar Surface Gravimeter", part of the Apollo Lunar Surface Experiments Package) on the Apollo 17 lunar mission. In the 1970s the results of his gravitational wave experiments were largely discredited, although Weber continued to argue that he had detected gravitational waves. He was the first to embrace gravitational waves as real and is considered the father of gravitational wave research.

Instead of Weber bars scientists turned to interferometry.

Laser Interferometry

Interferometry began with the Michelson Interferometer at the end of the 19th century. His interferometer used optical light. A Michelson interferometer minimally consists of mirrors M_1 and M_2 and a beam splitter M. In Figure 5 a source S emits light that hits the beam splitter (in this case, a plate beam splitter) surface M at point C. M is partially reflective, so part of the light is transmitted through to point B while some is reflected in the direction of A. Both beams recombine at point C' to produce an interference pattern incident on the detector at point E (or on the retina of a person's eye). As an undergraduate I built a Michelson Interferometer.

There are two 'arms' defining the two paths that the light follows. By moving the Mirrors one can change the length of the light paths. Rippling the spacetime along the arms causes them to alternately stretch and squeeze, so the signals arrive back at the detector at different times. Picture one arm stretching while the other arm squeezes, and *vice versa*.

A Fourier transform spectrometer is essentially a Michelson interferometer with one movable mirror. (A practical Fourier transform spectrometer would substitute corner cube reflectors for the flat mirrors of the conventional Michelson interferometer.) An interferogram is generated by making measurements of the signal at many discrete positions of the moving mirror. A Fourier transform converts the interferogram into an actual spectrum. There was an infrared Fourier transform spectrometer at the McMath Solar Telescope at Kitt Peak. We used it in the 1970s to obtain three dimensional spectra of the planet Uranus.

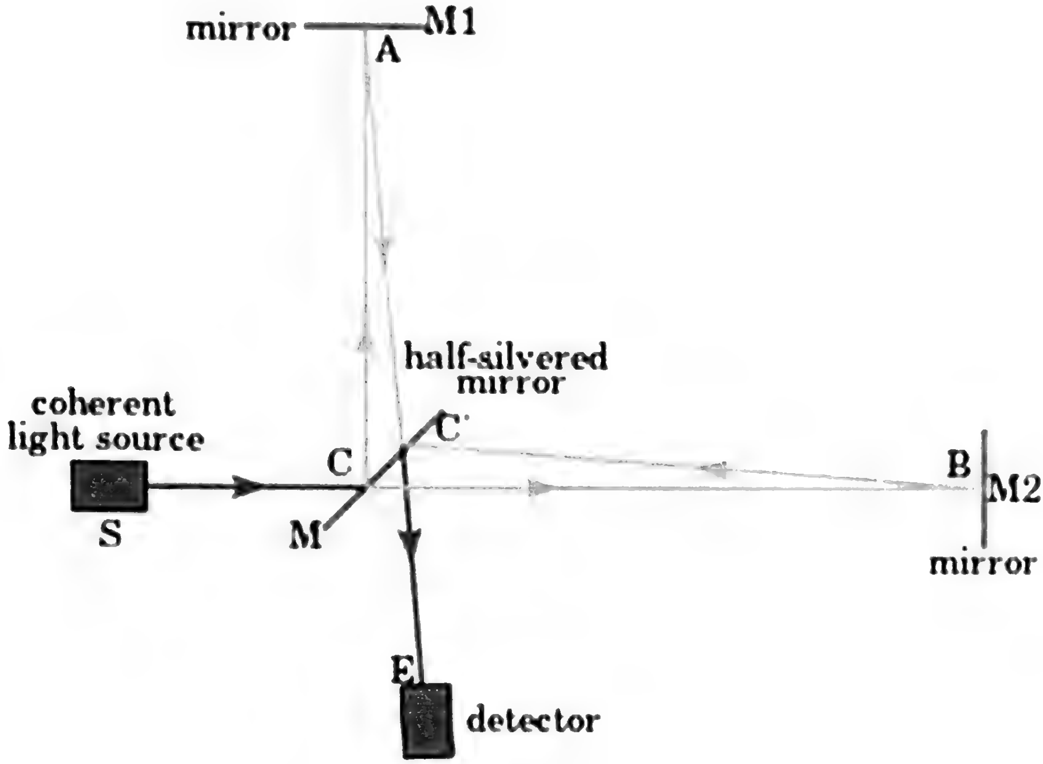

Figure 5 schematic of a Michelson Interferometer

Starting in the 1960s American scientists including Joseph Weber, as well as Soviet scientists Mikhail Gertsenshtein and Vladislav Pustovoit, conceived of basic ideas and prototypes of laser interferometry, and in 1967 Rainer Weiss of MIT published an analysis of interferometer use and initiated the construction of a prototype with military funding, but it was terminated before it could become operational. Then in 1968 Kip Thorne initiated theoretical efforts on gravitational waves and their sources at Caltech, and was convinced that gravitational wave detection would eventually succeed.

Laser Michelson interferometry is a leading method for the direct detection of gravitational waves. Detection involves measuring tiny strains in spacetime itself, affecting the two long arms of the interferometer unequally, due to a strong passing gravitational wave. Because a gravitational wave is a spacetime perturbation which propagates at the speed of light, the passing wave slightly curves the spacetime, which changes the local light path. Mathematically, if s the amplitude (assumed to be small) of the incoming gravitational wave and $L$the length of the optical

cavity in which the light is in circulation, the change of the optical path due to the gravitational wave is given by the formula:

$$\frac{\delta L}{L} = C \times h$$

with being a geometrical factor which depends on the relative orientation between the cavity and the direction of propagation of the incoming gravitational wave.

In 2015 the first detection of gravitational waves was accomplished using the LIGO instrument, a Michelson interferometer with 4 km arms. This was the first experimental validation of gravitational waves, predicted by Einstein's GTR. The most sensitive detector that accomplished the task possessed a sensitivity measurement of about one part in 5×10^{22} (as of 2012) provided by the LIGO and VIRGO observatories.

LIGO and VIRGO

LIGO

Two large observatories were built in the United States with the goal of detecting gravitational waves using laser interferometry. These observatories can detect a change in the 4 km mirror spacing of less than a ten-thousandth the charge diameter of a proton, equivalent to measuring the distance to Proxima Centauri with an accuracy smaller than the width of a human hair.

The initial LIGO observatories were funded by the National Science Foundation (NSF) and were conceived, built, and operated by Caltech and MIT. In 1994 with a budget of USD 395 million, LIGO stood as the largest overall funded NSF project in history.

After a rocky start the LIGO project broke ground in Hanford, Washington in late 1994 and in Livingston, Louisiana in 1995. They collected data from 2002 to 2010 but no gravitational waves were detected.

The Advanced LIGO Project to enhance the original LIGO detectors began in 2008 and continues to be supported by the NSF, with important contributions from the UK Science and Technology Facilities Council, the Max Planck Society of Germany, and the Australian Research Council. The improved detectors began operation in 2015.

The redesign made LIGO's new interferometers 10 times more sensitive than the original. A 10-fold increase in sensitivity means that the new and improved LIGO will ultimately be able to listen for gravitational waves 10 times farther away than Initial LIGO (iLIGO). This is an enormous improvement since listening 10 times farther away will give LIGO access to 1000 times more volume of space (volume increases with the cube of the distance. So 10 times farther away means 10×10×10=1000 times the volume of space), and 1000 times more galaxies that host sources of gravitational waves. Figure 6 illustrates the change in volume.

Figure 6 An illustration of a 10 times change in radius

LIGO's multi-kilometer-scale gravitational wave detectors use laser interferometry to measure the minute ripples in spacetime caused by passing gravitational waves from cataclysmic cosmic sources such as the mergers of pairs of neutron stars or black holes, or supernovae. LIGO consists of two widely separated interferometers within the United States—one in Hanford, Washington and the other in Livingston, Louisiana—operated in unison to detect gravitational waves.

Although it is considered one observatory, LIGO is comprised of four distinct facilities across the United States: two gravitational wave

detectors (the interferometers) and two university research centers. The interferometers are located in fairly isolated areas of Washington (LIGO Hanford) and Louisiana (LIGO Livingston), and separated by 3,002 km (1,865 miles). The two primary research centers are located at The California Institute of Technology (Caltech) in Pasadena, California, and The Massachusetts Institute of Technology (MIT) in Cambridge, Massachusetts. Figure 7 is a schematic of the LIGO interferometer.

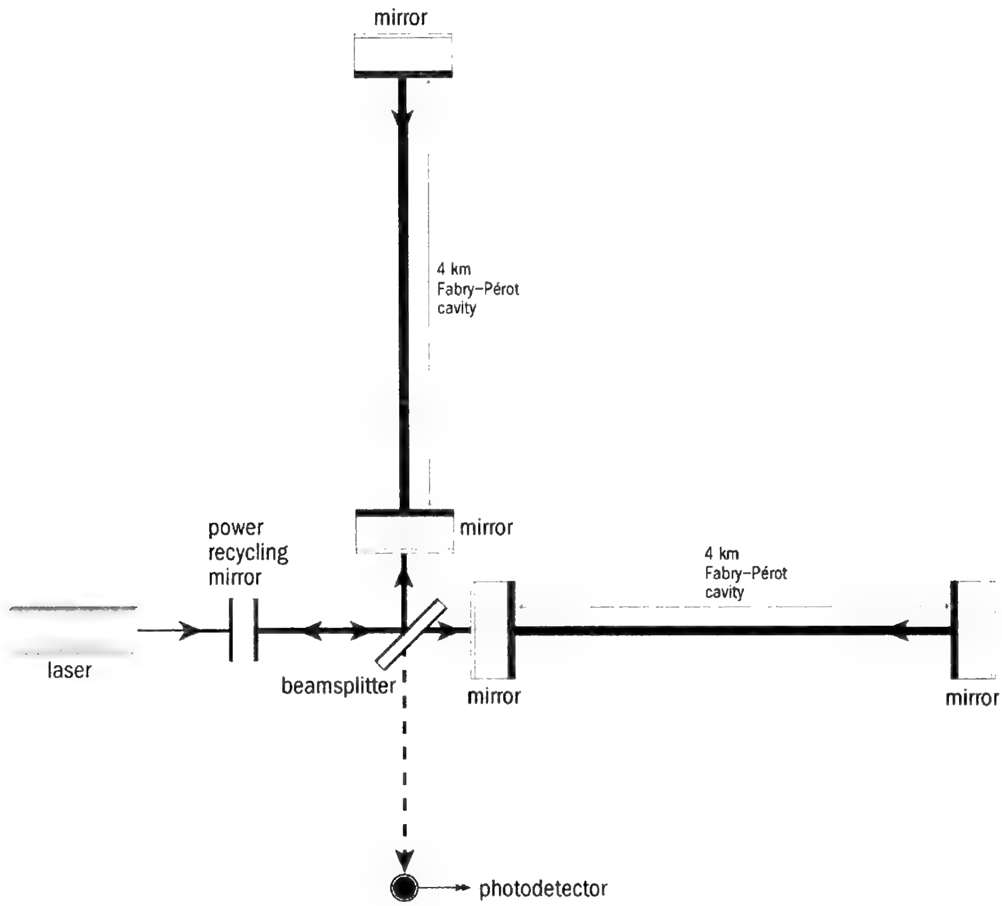

Figure 7 a schematic of LIGO

LIGO is a national facility for gravitational-wave research, providing opportunities for the broader scientific community to participate in detector development, observation, and data analysis. The capabilities of the LIGO detectors were greatly improved with the completion of the Advanced LIGO project in late 2014. The Advanced LIGO detectors will

increase the sensitivity and observational range of LIGO by a factor of 10 over its predecessor.

Richard Muller said "Gravitational waves are what happens when you shake space itself. Just like when you shake a rope, the shake moves down the rope, when you shake space, the shake travels. When it passes by two mirrors, the distance between them changes (because space is being shook), and that's what LIGO detects – a change in the distance between two mirrors."

LIGO consists of:

- Two L-shaped detectors with 4 km long vacuum chambers...
- built 3000 kilometers apart and operating in unison...
- to measure a motion 10,000 times smaller than an atomic nucleus
- caused by the violent and cataclysmic events in the Universe...
- occurring millions or billions of light years away.

Encapsulating 10,000 m^3 (350,000 ft^3), each vacuum chamber encloses as much volume as 11 Boeing 747-400 commercial airliners. The air removed from each of LIGO's vacuum chambers could inflate two-and-a-half million footballs, or 1.8 million soccer balls. LIGO's vacuum volume is surpassed only by the Large Hadron Collider in Switzerland.

The pressure inside LIGO's vacuum tubes is one-trillionth of an atmosphere (10^{-9} tor). It took 40 days (1100 hours) to remove all 10,000 m^3 (353,000 ft^3) of air and other residual gases from each of LIGO's vacuum tubes to reach that pressure.

LIGO's arms are so long that the curvature of the Earth is a measurable 1 meter (vertical) over the 4 km length of each arm. The most precise concrete pouring and leveling imaginable was required to counteract this curvature and ensure that LIGO's vacuum chambers were flat and level. Without this work LIGO's lasers would hit the end of each arm 1 m above the mirrors. Figure 8 is an aerial photo of LIGO.

Figure 8 aerial photo of LIGO

VIRGO

The Virgo interferometer is also a large Michelson interferometer designed to detect gravitational waves predicted by GTR. It is isolated from external disturbances: its mirrors and instrumentation are suspended and its laser beam operates in a vacuum. The instrument's two arms are three kilometers long and located near Pisa, Italy.

The Virgo project was approved in 1993 by the French and in 1994 by Italy. The construction of the detector started in 1996. In 2000 they created the European Gravitational Observatory (EGO consortium). EGO is responsible for the Virgo site, in charge of the construction, the maintenance and the operation of the detector, as well as of its upgrades. The goal of EGO is also to promote research and studies about gravitation in Europe. By December 2015 19 laboratories plus EGO were members of the Virgo collaboration.

The initial Virgo detector was not sensitive enough to detect a gravitational wave. Therefore, it was decommissioned in 2011 to be replaced by the "advanced" Virgo detector which aims at increasing its sensitivity by a factor of 10. The advanced Virgo detector benefits from the experience gained on the initial detector and from technological advances since it was made.

Since 2007 Virgo and LIGO have agreed to share and jointly analyze the data recorded by their detectors and to jointly publish their results.

Because the interferometric detectors are not directional (they survey the whole sky) and they are looking for signals which are weak and infrequent, simultaneous detection of a gravitational wave in multiple instruments is necessary to confirm the signal and determine its origin.

Noise

How do the scientists know that a signal in the data really came from an event in space? This consumes a huge portion of the work that is done by many of the scientists and engineers – separating a gravitational wave vibration from all the other vibrations the detectors feel. To confirm a detection they use several techniques to help sift through the noise, including:

- Measuring all known noise sources (*e.g.* earthquakes, winds, ocean waves, trucks driving by on nearby roads, farming activities, even molecular vibrations in LIGO's mirrors) with seismometers, magnetometers, microphones, and gamma ray detectors, and then filtering out the signals caused by these noise sources from the data.
- Looking for identical, simultaneous signals from multiple detectors world-wide (LIGO, Virgo). This rules out noise sources which are local to a given detector. The more detectors that feel the same vibration at the same time (accounting for a gravitational-wave's travel time between detectors), the more certain they are that the source of the vibration was not local.
- Using sophisticated analysis techniques to filter out and separate noise from a potential signal.
- Comparing the signals received with theorized patterns of gravitational waves generated by known phenomena.
- Confirming the timing of the possible gravitational wave event with astronomical observatories, hoping to see a coincident EM event on the sky (*e.g.* light from a supernova explosion).

Despite these precautions, however, no measuring device is 100% accurate or precise, so no result of an experiment is ever 100% certain. For LIGO they would like to be more than 99.9999% sure that a possible detection was not just noise.

Once they start to see signals on a regular basis in conjunction with other observations and other observatories around the world, confidence

that they are truly detecting gravitational waves will grow until any uncertainties will be too small to worry about.

Once LIGO and VIRGO begin detecting gravitational waves on a regular basis, the data will be used to answer outstanding questions about astronomy and the Universe in general. Since each source of gravitational waves plays a unique “tune”, the first thing to learn is which event in the Universe generated the wave. The known possibilities are:

- The merging (coalescence) of two black-holes, or two neutron stars, or a neutron star and a black hole in orbit around each other
- The vibration or rotation of a bumpy neutron star
- The explosion of a lumpy supernova (if a star is not perfectly spherical when it explodes)
- Motions of matter and energy right after the Big Bang.

And there’s always a chance finding something as yet unknown.

Detection

The first detection of gravitational waves was reported in 2016 by the LIGO Scientific Collaboration (LSC) and the Virgo Collaboration with the international participation of scientists from several universities and research institutions. Scientists involved in the project and the analysis of the data for gravitational-wave astronomy are organized by the LSC, which includes more than 1000 scientists worldwide as of December 2016.

When in Observing mode, the Hanford and Livingston detectors collect data simultaneously, operating as one single observatory. This coordination is essential to LIGO’s ability to verify a gravitational-wave detection, and was critical to LIGO confirming the world’s first detection of gravitational waves emitted by two colliding black holes 1.3 billion light years away.

LIGO began observing in September, 2015 and within days LIGO’s new advanced detectors achieved what iLIGO could not accomplish in eight years of operation: On September 14, 2015, the LIGO detectors in Livingston, LA and Hanford, WA made the world’s first direct detection of gravitational waves, heralding a new era in astronomical exploration. The signal was named GW150914 from ‘Gravitational Wave’ and the date of observation. The gravitational waves detected by LIGO on that day were

generated by two black holes colliding and merging into one nearly 1.3 billion light years away. Figures 9, 10, and 11 show what the detection looked like. Note the rapid increase in amplitude at the merger.

The gravitational waves detected by LIGO on September 14, 2015 were generated by the merger of two massive black holes. Not only was this the world's first detection of gravitational waves, but it was also the first time black holes were directly 'observed', the first time black holes of this particular size were observed, and also the first confirmation that binary black holes (two black holes orbiting each other) exist at all.

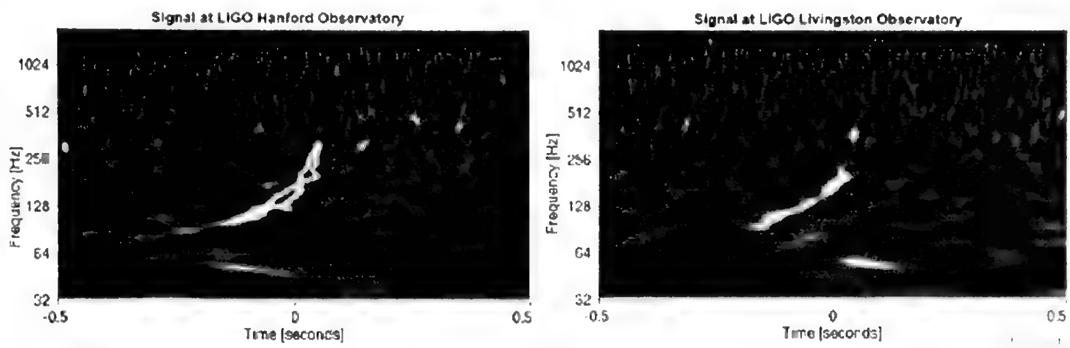

Figure 9 the September 2015 detection of the gravitational wave produced by two colliding and merging black holes

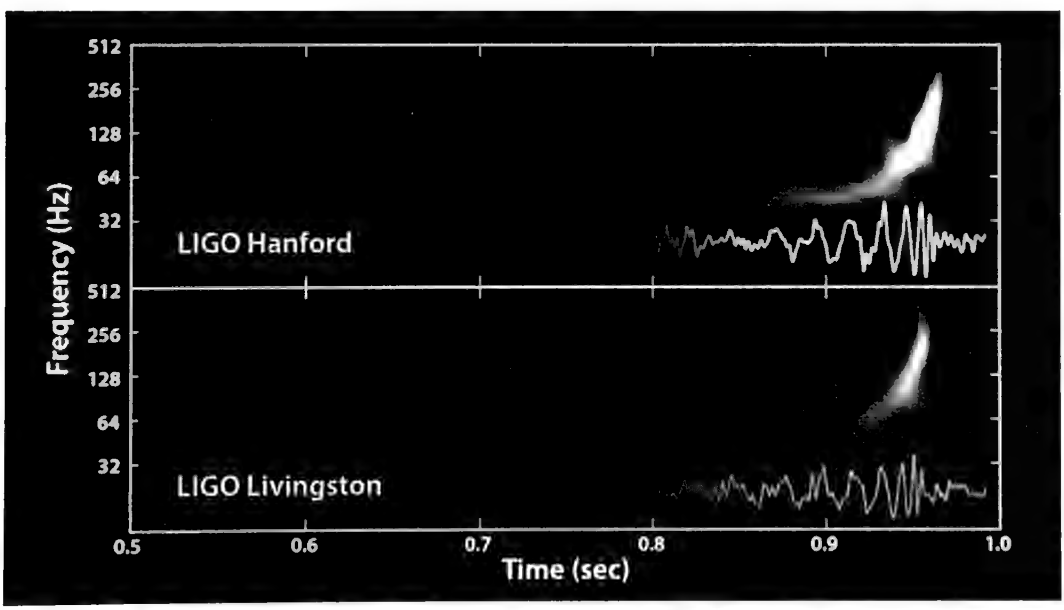

Figure 10 the September 2015 detection of the gravitational wave produced by two colliding and merging black holes

The change in arm length occurred faster and faster as the wave passed – short-long, short-long, short-long. If the oscillation is tuned to an audible frequency the final signal sounds like a fast chirp. Imagine a silver dollar spinning on a tabletop. As the coin starts to wobble around its outer edge, making a "blop…blop…blop" sound that speeds up (blop-blop-blop) and speeds up (blopblopblop) until it's just a blur of sound that rises in pitch into a final "blooop" as the coin flattens on the table. That final "blooop" is the chirp of the final moment of the merger.

During the final fraction of a second, the two black holes collided into each other at nearly one–half the speed of light and formed a single more massive black hole, converting a portion of the combined black holes' mass to energy, according to Einstein's famous formula

$$E = mc^2 .$$

This energy is emitted as a final strong burst of gravitational waves. It is these gravitational waves that LIGO had observed.

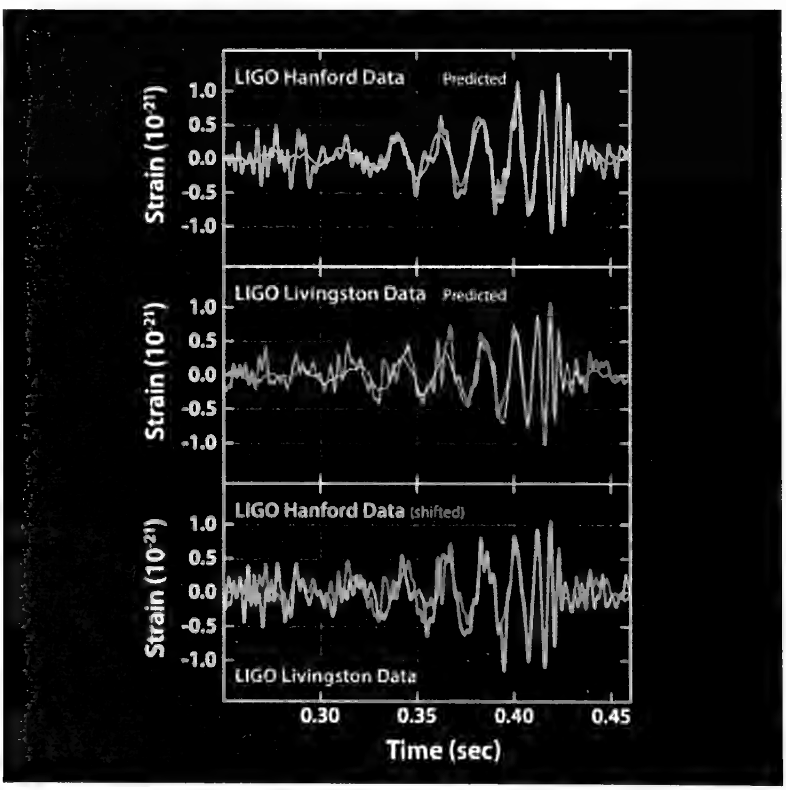

Figure 11 processed data from event

Based on the observed signals, LIGO scientists estimate that the black holes for this event were about 29 and 36 times the mass of the Sun, and the event took place 1.3 billion years ago. About three times the mass of the Sun was converted into gravitational waves in a fraction of a second—with a peak power output about 50 times that of the whole visible universe. By looking at the time of arrival of the signals — the detector in Livingston recorded the event 7 milliseconds before the detector in Hanford — so they can say that the source was located in the Southern Hemisphere of the sky.

According to the press release "Our observation of gravitational waves accomplishes an ambitious goal set out over five decades ago to directly detect this elusive phenomenon and better understand the universe, and, fittingly, fulfills Einstein's legacy on the 100th anniversary of his general theory of relativity," says Caltech's David H. Reitze, executive director of the LIGO Laboratory.

There's More

As of August 2017 LIGO had made five detections of gravitational waves, the first four of which were colliding black hole pairs. The fifth detected event, on August 17, 2017, was the first detection of a collision of two neutron stars, GW 170871, which simultaneously produced signals detectable by conventional telescopes.

Neutron stars are so-called because their matter is so densely packed that they are composed primarily of neutrons. One such star possessing the mass of our Sun would be just 10 to 15 km in diameter. Using the signals received in LIGO's detectors, the masses of the neutron stars were determined to 1.1 to 1.6 times as massive as our Sun.

LIGO Hanford Observatory (LHO) Head, Michael Landry explained what LIGO saw in its detectors. "LIGO and Virgo detected 100 seconds of gravitational waves as these two neutron stars spiraled together in a massive and fiery collision," he said. "In a sprawling follow-up campaign involving about one-quarter of the world's professional astronomers, observatories in space and on the Earth have detected radiation in all wavelengths from gamma rays to radio waves. But the LIGO and Virgo detectors were absolutely essential in identifying and pinpointing the event in the sky, allowing this campaign to proceed", Landry added.

While black hole collisions produce almost no signature other than gravitational waves, the collision of neutron stars can be — and was — observed up and down the EM spectrum. "When neutron stars collide, all hell breaks loose," said Frans Pretorius, a Princeton physics professor. "They start producing a tremendous amount of visible light, and also gamma rays, x-rays, radio waves…." The gravitational waves were the first evidence of the neutron star merger to arrive at Earth, followed by a gamma ray burst that arrived 1.7 seconds later.

The connection between neutron stars and gamma ray bursts (GRBs) was first put forth thirty years ago in a pair of papers by Bohdan Paczynski and Jeremy Goodman of Princeton University. They argued that colliding neutron stars could be the sources of GRBs, first identified by satellites in the late 1960s. In addition Paczynski had realized that most GRBs were coming from distances far enough that the expansion of the universe was affecting their apparent distribution.

"Bohdan Paczynski was absolutely right," said Goodman. However, his ideas were not immediately embraced by the field. Goodman said "I remember going to a conference in Taos, New Mexico. … Bohdan gave a short talk on his idea that GRBs are coming from cosmological distances. I remember these other astrophysicists … they were respectfully quiet when he spoke, but regarded him as a bit of a lunatic." I, too, was at that conference in Taos.

LIGO scientists were alerted to a remarkable astronomical event, which occurred within 2 seconds of LIGO's detection of the colliding neutron stars. The Fermi gamma ray space telescope had recorded a "short" gamma ray burst (sGRB) just 1.7 seconds after the arrival of the gravitational waves. This is GRB 170817A.

Gamma ray bursts are seen quite frequently, but what causes them has remained a mystery. Knowing that neutron star mergers were expected to generate electromagnetic radiation, likely of very high energy, excitement grew as it became more and more plausible that the first electromagnetic counterpart to a gravitational wave (GW) had been observed. The time of arrival of the sGRB and GW signals was especially telling, and important to validating the relationship between them. Paczynski was right.

Other wavelengths soon joined in. The first 'S' in SSS17a (supernova survey) stands for the Swope 1-m telescope Boller & Chivens reflector at Las Campanas. It produced the important first detection of the optical transient after the gravitational wave trigger. A transient and fading optical source occurred 10.9 hours after the gravitational wave trigger, Swope Supernova Survey 2017a (SSS17a), coincident with GW170817. SSS17a is located in NGC 4993, an S0 galaxy at a distance of 40 megaparsecs. The precise location of GW170817 provides an opportunity to probe the nature of these cataclysmic events by combining EM and gravitational-wave observations. Figure 12 shows a Hubble Space Telescope image taken before the trigger and the Swope Telescope image of the signal after the trigger.

When neutron stars smash into each other at an appreciable fraction of the speed of light, the collision fuses atoms together and creates the elements that fill the bottom rows of the periodic table.

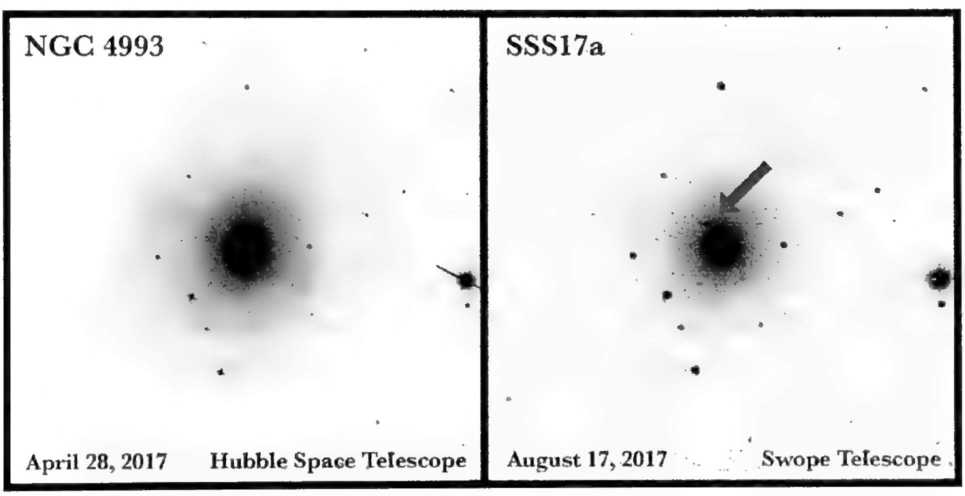

Figure 12 on the left is a Hubble image of the galaxy before the event and on the right is the same galaxy after the event with optical transient indicated by the arrow

"These elements—platinum, gold, uranium, and many other less valuable ones that are high up on the periodic table — they have more neutrons than protons in their nuclei," Goodman said. "You can't get to those nuclei in the same way that we understand elements up to iron being produced, by effectively adding one neutron at a time. The problem is that you have to add a lot of neutrons very quickly." This rapid process is known as the r-process.

For a long time scientists thought that r-process elements were created in supernovae, but the numbers didn't add up, Goodman said. "But neutron stars are mostly neutrons, and if you smash two of them together, it's reasonable to expect that some of the neutrons will splash out."

Spectroscopic observations from the European Southern Observatory's Very Large Telescope (VLT) in the wake of the LIGO detection confirmed that heavy metals like platinum, lead, and gold were created in the collision of the two neutron stars.

The VLT data used to identify these elements, the visible and near-visible wavelengths of light, were gathered in the hours and days following LIGO's detection of the gravitational waves. Once word had begun to spread of LIGO's discovery, the worldwide astronomical community trained their telescopes and other instruments on the patch of sky that the gravitational waves had come from. There are almost 4000 co-authors on the paper describing the follow-up observations of x-rays, gamma rays, visible light waves, radio waves, and more.

The team reported a measurement of the Hubble constant that combines the distance to the source inferred purely from the gravitational-wave signal with the recession velocity inferred from measurements of the redshift using the EM data. They find a value of 70^{+12}_{-8} km/s/Mpc. A binary coalescence — such as the merger of two neutron stars — is a self-calibrating 'standard candle', which means that it is possible to infer directly the distance without using the cosmic distance ladder. The key is that the rate at which the binary's frequency changes is directly related to the amplitude of the gravitational waves it produces, *i.e.* how 'loud' the GW signal is. Just as the observed brightness of a star depends on both its intrinsic luminosity and how far away it is, the strength of the gravitational waves received at LIGO depends on both the intrinsic loudness of the source and how far away it is. By observing the waves with detectors like LIGO and Virgo, we can determine both the intrinsic loudness of the gravitational waves as well as their loudness at the Earth. This allows us to directly determine distance to the source which give the Hubble constant. For a list of various observations of the Hubble constant see https://en.wikipedia.org/wiki/Hubble%27s_law#Observed_values .

Conclusion

The direct detection of gravitational waves requires multiple detections from widely separated sites. To enhance detection capabilities, LIGO researchers are working closely with gravitational wave researchers at Virgo in Italy and GEO600[x] in Germany, they are assisting the Japanese as they build KAGRA, and for years LIGO staff have been training Indian engineers to prepare for the construction of the third LIGO interferometer in India.

Now that LIGO has detected gravitational waves, the next steps in the emerging field of gravitational wave astronomy will involve beginning to understand the nature, dynamics, and structure of gravitational wave sources. The ultimate goal (not yet achieved) is to use a world-wide network of gravitational wave detectors to pinpoint quickly and precisely the location of gravitational wave sources on the sky so that LIGO's astronomical partners can immediately participate in the search to unshroud the sources of these enigmatic vibrations in spacetime. Optical, x-ray, radio, infrared, and gamma ray telescopes, as well as neutrino detectors are at the ready. This 'multi-messenger' astronomy represents one of the large collaborations that LIGO and other detectors will help to facilitate amongst the global scientific community.

Check out these leisure-time activities that you can try alone or with friends.

- **Gravity Spy!** Help LIGO scientists search for gravitational waves by finding different kinds of "glitches" found in real LIGO data. By identifying glitches, you will help train LIGO's computers to find gravitational wave signals more efficiently! Visit https://www.zooniverse.org/projects.zooninverse/gravity-spy
- **Build an interferometer** https://dcc.ligo.org/LIGO-T1400762/public and https://dcc.ligo.org/LIGO-T0900393/public
- **Black Hole Hunter** http://blackholehunter.org/
- **Black Hole Pong** http://www.gwoptics.org/processing/blackhole_pong/
- **Space-time Quest** https://www.laserlabs.org/spacetimequest.php
- **American Museum of Natural History Virtual Interferometer** https://www.amnh.org/explore/science-

bulletins/%28watch%29/astro/documentaries/gravity-making-waves (Click "Interactive: Operate LIGO!")

- **Einstein@Home** https://einsteinathome.org/ Use your computer's idle time to search for gravitational waves.

Bio

Sethanne Howard is an astrophysicist retired from the US Naval Observatory where she was Chief of the Nautical Almanac Office. All the information in this paper came from Wikipedia and the LIGO web site.

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[i] Newton connected force and momentum: F = d(mv)/dt in 3 dimensions to represent his universe. At very low speeds and low mass Einstein's equation reduce to those of Newton.

[ii] The Lorentz transformations are coordinate transformations between two coordinate frames that move at constant velocity relative to each other. Frames of reference can be divided into two groups: inertial (relative motion with constant velocity) and non-inertial (accelerating in curved paths, rotational motion with constant angular velocity, etc.). The term "Lorentz transformations" only refers to transformations between inertial frames. They supersede the Galilean transformation of Newtonian physics, which assumes an absolute space and time.

[iii] Consistent with Euclid.

[iv] Christoffel symbols provide a concrete representation of the connection of (pseudo-) *Riemannian* geometry in terms of coordinates on the manifold.

[v] Hawking, S. W. & Israel, W. (1979). *General Relativity: an Einstein Centenary Survey.* Cambridge: Cambridge University Press.

[vi] This is one of the largest radio telescopes, not the largest, but one of the largest. The telescope appeared in a James Bond movie.

[vii] A neutron star is quite unusual. It is composed of almost all neutrons densely packed. They are the smallest and densest stars known to exist. A matchbox filled with neutron star matter will weigh 3 billion tons. A pulsar is a neutron star that emits a narrow beam of EM radiation. The beam spins with the pulsar.

[viii] In other words the pulse travels a distance of 3 light seconds extra.

[ix] Binary stars offer advantages over a single star. Once can determine the mass of each star and other properties.

[x] GEO600 is a ground-based interferometric gravitational wave detector located near Hannover, Germany. It is designed and operated by scientists from the Max Planck Institute for Gravitational Physics and the Leibniz Universität Hannover, along with partners in the United Kingdom, and is funded by the Max Planck Society and the Science and Technology Facilities Council (STFC).

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